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SOLAR DYNAMIC POWER SYSTEMS FOR SPACE STATION

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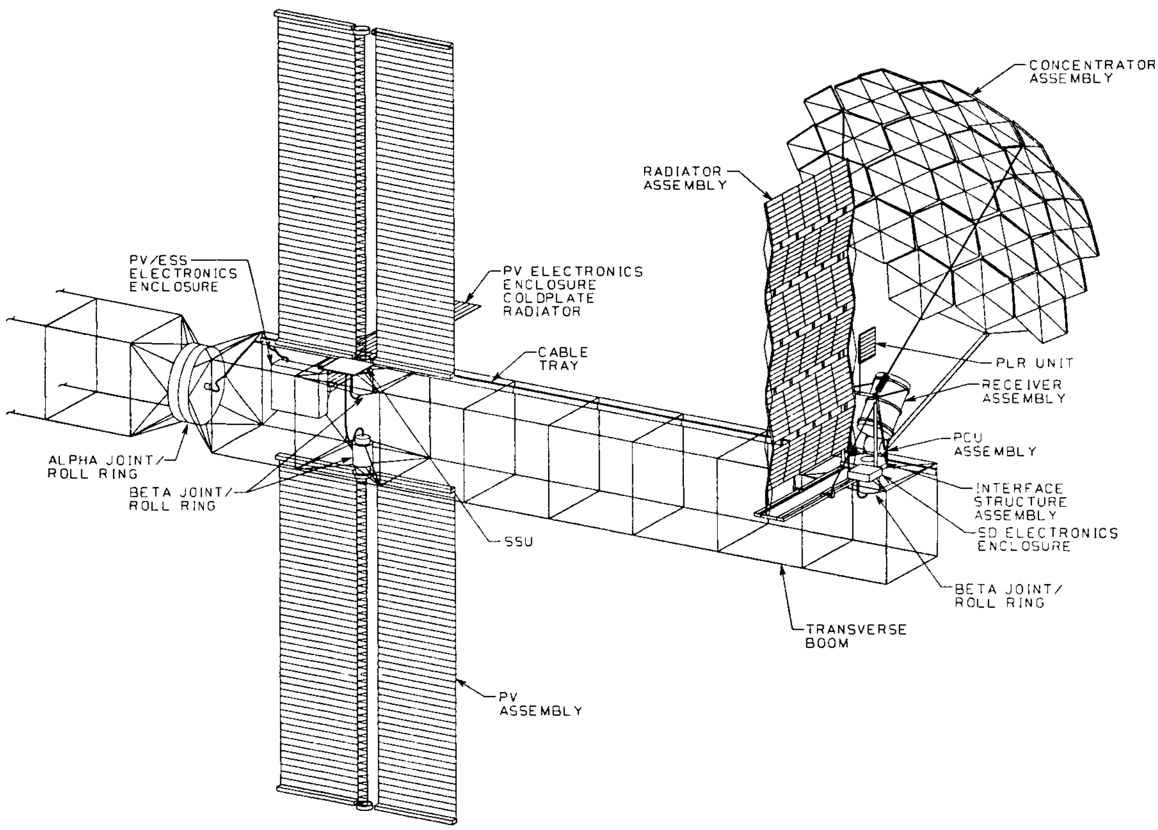
OBJECTIVE

Solar dynamic systems studies and development are currently being performed by NASA Lewis Research Center and their Space Station Program Phase B and Advanced Development Program Contractors to complete preliminary design of a viable solar dynamic power module. This design must be compatible with a Space Shuttle launch and with on-orbit assembly aboard the Space Station.



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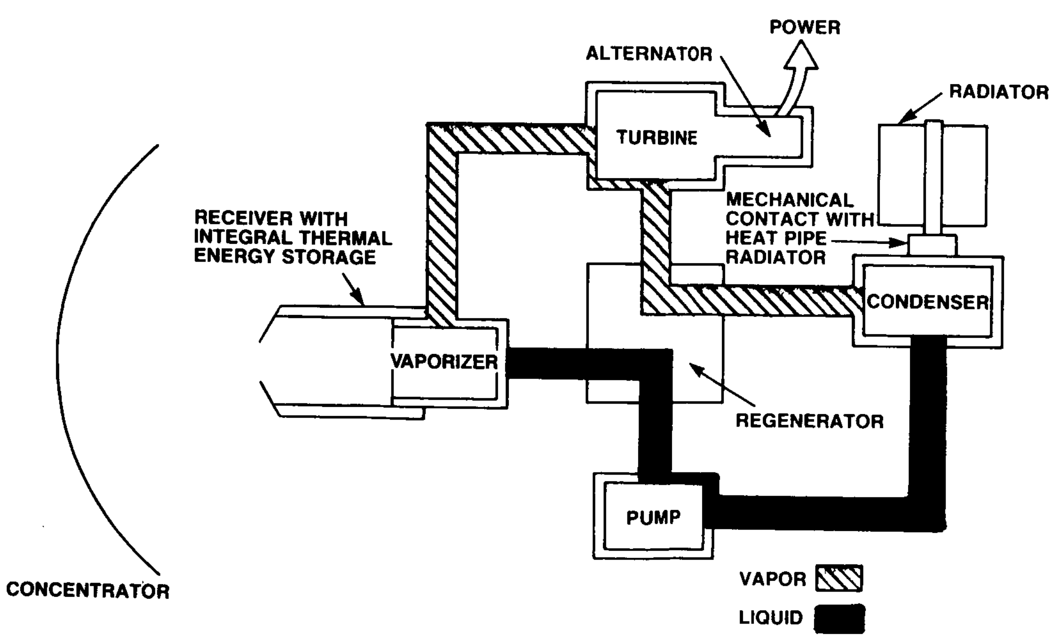
BACKGROUND

Solar dynamic power systems work by accurately pointing a reflector (concentrator towards the sun and focusing the reflected energy into a heat receiver where a working fluid is heated. This heated fluid is used to drive a turbine in a power conversion unit. Coupled to the turbine is an alternator which generates electricity thus completing the conversion of thermal to mechanical to electrical energy. The working fluid is cooled by a dedicated thermal control system (heat exchanger/radiator) in order to maintain proper thermodynamic state points. Both Organic Rankine Cycle and Closed Brayton Cycle heat engines are under consideration as potential "power plants" of the solar dynamic system.

Two solar dynamic power modules are utilized on the IOC Space Station. Each module is capable of delivering to the user's load converter an average of 25 kWe over the 90 to 95 minute Space Station orbit. During the 34.18 to 35.47 minute eclipse portion of the orbit, a thermal energy storage (TES) medium is required to heat the working fluid. A TES medium integral to the receiver has been proposed and is being pursued during preliminary design.

In order to achieve the appropriate flux distribution in the receiver cavity, concentrator mirror surface accuracy and pointing accuracy tolerances are tightly controlled. Structural integrity is required in the Space Station truss system, solar dynamic module interface and support structures and the concentrator substrate. To achieve required concentrator surface accuracies, very stringent manufacturing tolerances must be applied to the reflector design. In addition, active control of the vernier pointing capability is necessary to provide the required pointing accuracy.



• **Solar Dynamic ORC Is a Simple Energy Conversion Cycle**

SCOPE AND APPROACH

A solar dynamic module conceptual design was generated during the Space Station Program WP-04 Phase B: Space Station Definition and Preliminary Design. Preliminary design based upon this conceptual design, discussed later, is currently being conducted.

Structural and control issues were among the many discriminators included in trade studies used to arrive at a baseline conceptual design. Finite element method static and dynamic analyses and control theory calculations were used to assess the structural characteristics of competing design concepts. Normal mode analysis was used to determine structural frequencies of the Space Station transverse boom given different solar dynamic module designs. Control theory was then used to predict system instabilities given the structural and controller bandwidths.

Presented herein is a summary of the structures and controls studies used to aid in the selection of a Space Station solar dynamic module design.

- Solar Dynamic Module Conceptual Design Trade Studies
  - Controls/Structures Interaction Discriminator
    * Normal modes analysis of solar dynamic module conceptual designs using MSC/NASTRAN
    * Classical control theory used to evaluate solar concentrator coarse and vernier pointing system
    * Static and dynamic finite element analysis used to evaluate module support and transition structures

OUTLINE

Several different classes of solar concentrators were considered during the early stages of Phase B: Definition and Preliminary Design Studies. These options included single and multiple reflection systems and refraction systems. Simple and offset parabolic reflectors, selected as the best candidate designs, were studied by using structural normal modes analysis to determine the coupled solar dynamic module - transverse boom natural frequencies. The Space Station was modelled as a lumped parameter system to determine the control system stability.

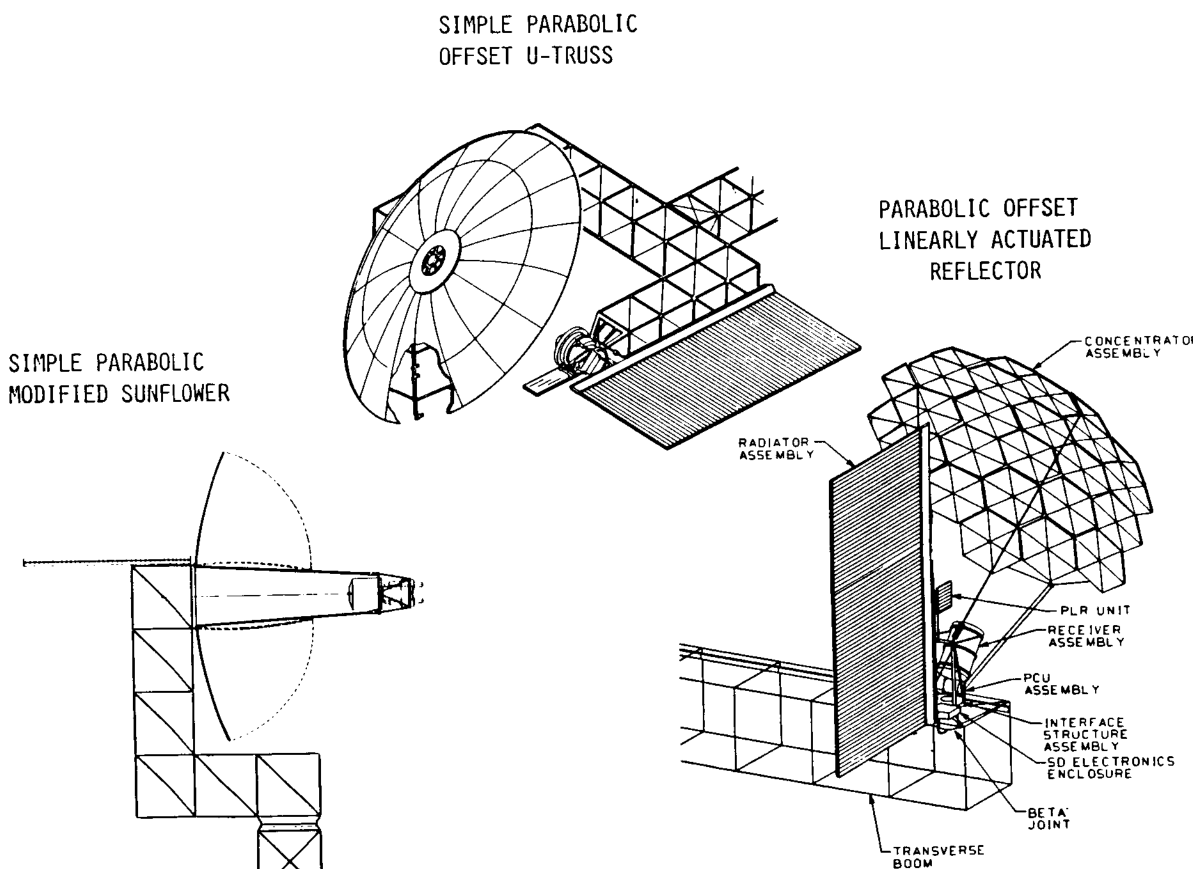
The Parabolic Offset Linearly Actuated Reflector (POLAR) concept was chosen as the concept with which to go forward into preliminary design. The interface and support structure for this concept are currently being studied.

- Conceptual Designs
- Normal Modes Analysis
- Pointing Control and Coupling Analysis
- The Parabolic Offset Linearly Actuated Reflector
- Support Structure Design and Analysis
- Summary

CONCEPTUAL DESIGNS

A number of concentrator optical systems were considered during trade studies. These included, but were not limited to, symmetric Newtonian (parabolic), offset Newtonian, Cassegrainian, Fresnel refractor, and point focus trough designs. Key discriminators in determining the optical system included mass, drag, mass moment of inertia about the transverse boom, launch cost, development cost, annual cost, life-cycle cost, maintainability, logistics, safety, technology readiness, and IOC schedule/cost risk. Based primarily upon technology readiness and IOC schedule/cost risk, all but the symmetric and offset Newtonian concentrator designs were eliminated.

Three proposed design concepts studied in detail and shown in the figure are the modified sunflower deployable concentrator (simple Newtonian), the Offset U-Truss configuration (simple Newtonian), and the Parabolic Offset Linearly Actuated Reflector (POLAR) system (offset Newtonian).



NORMAL MODES ANALYSIS

The finite element method (Ref. 1) was used to model the three solar dynamic module concepts under consideration, the modified sunflower, the POLAR, and the offset U-Truss. Continuous beam representations of the truss work (Ref. 2) and concentrated mass representations of the major components of the solar dynamic module were employed. Masses and dimensions of representative Closed Brayton Cycle solar dynamic module major components were used in this analysis and are listed below.

The length of the transverse boom was determined by shadowing considerations. The required spacing between the solar dynamic module and the vertical keel or between adjacent solar dynamic modules is set by the width of the solar concentrator and the maximum beta angle. Maximum beta is the addition of the orbit inclination and the seasonal rotation of the earth. For the analysis performed, the distance between the transverse boom/vertical keel intersection and solar dynamic module center line was 63 ft. The distance between adjacent solar dynamic modules for the growth configurations was 107.36 ft. This spacing was based upon a maximum beta joint of 55°.

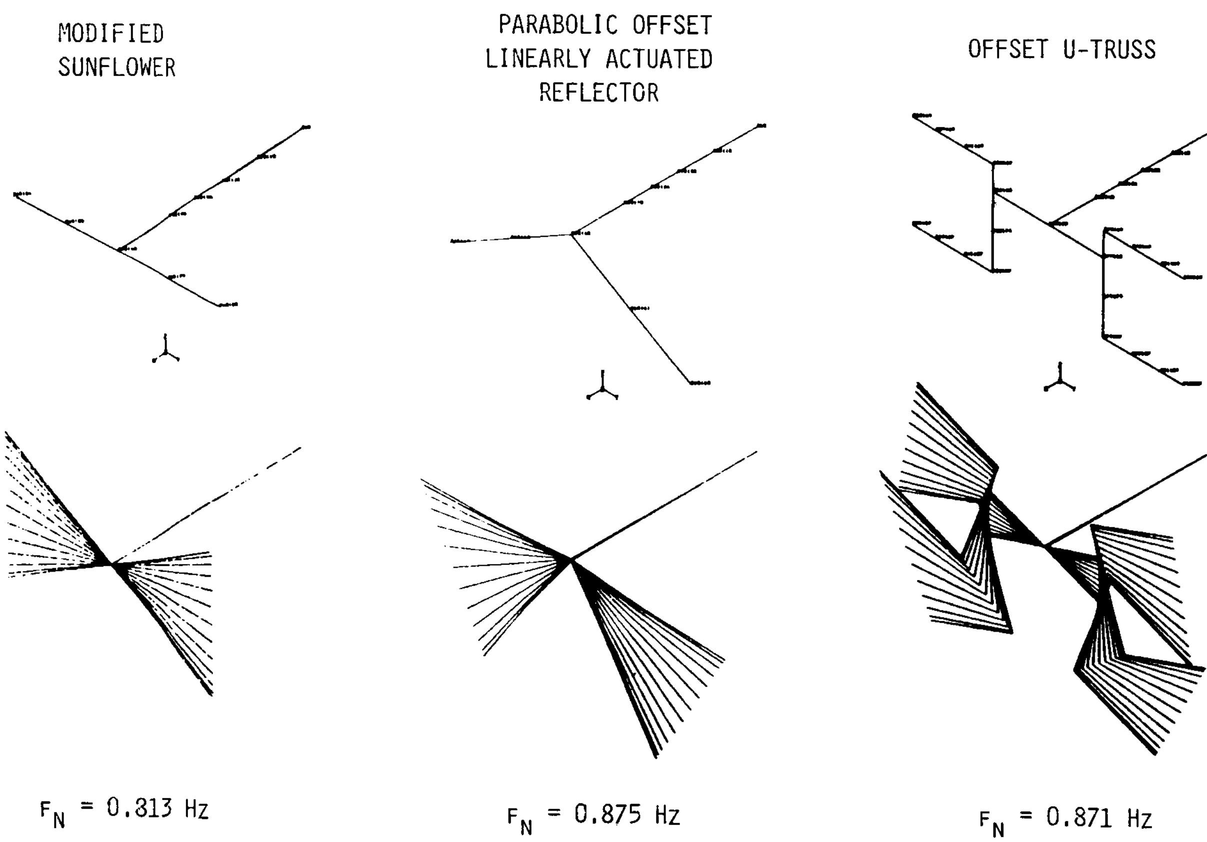
Closed Brayton Cycle (25 kWe SD Module)

Component	Mass (lbs.)	On-Orbit Dimensions (ft)
Concentrator	1684	43.32 equiv dia
Receiver Including Eclipse TES	2860	6.67 dia x 7.92 length
PCU	1075	2.19 dia x 2.52 length
Radiator Panels (40 req'd) Heat Exchanger	3400	req'd area = 1000 sq ft width - 1. , thickness - .125 , length - 28. width - 3. , height - 2. , length - 45.
TOTAL	9019	

Normal modes analysis was performed on each Closed Brayton Cycle solar dynamic module concept for three different cases. These cases were 100 kWe, 200 kWe, and 300 kWe Space Station models using replications of 25 kWe solar dynamic modules. The cases run were of the half transverse boom where the transverse boom/vertical keel interface was assumed fixed in all translations and rotations.

This simplified the problem significantly by reducing a substantial number of degrees of freedom that would ordinarily be assigned to define the entire dual-keel Space Station. It also allowed for the isolation of the transverse boom and its natural frequencies. The transverse boom torsional mode frequency is of particular interest because it is the structural frequency that could potentially couple with the alpha joint controller.

The natural frequencies and corresponding mode shapes for the fundamental torsional mode are shown in the figure below.

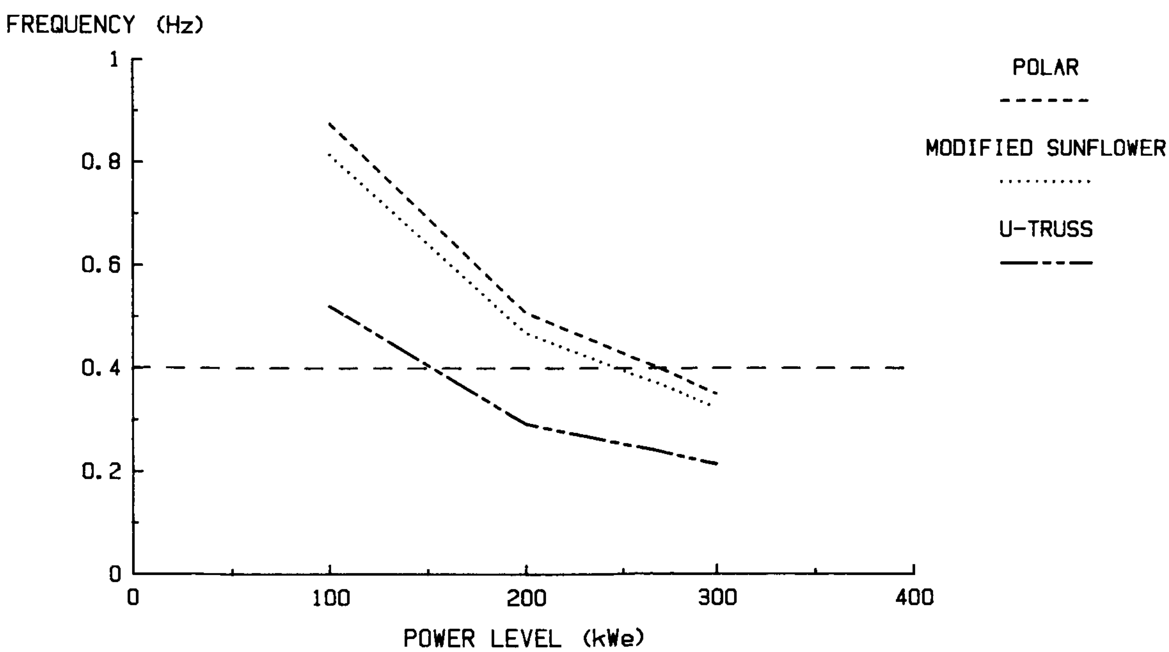


LOWEST TRANSVERSE BOOM TORSIONAL MODE NATURAL FREQUENCY

(ALL SD IOC CONFIGURATION)

Results of the transverse boom fundamental torsional mode natural frequency dependency on solar dynamic module design are summarized in the figure. All SD module designs exhibit the same general trend of frequency reduction in transverse boom torsion as the station power level increases. This frequency reduction is due to the increase in the mass of the system as the transverse boom is lengthened and the additional power modules are added. The actual frequency values of the POLAR conceptual design were found to be quite close to the values of the modified sunflower design at the power levels of 100 kWe, 200 kWe, and 300 kWe. The transverse boom fundamental torsional mode natural frequencies determined for both of these concepts appear to have adequate separation (ten times or greater) between the structural and controller bandwidth frequencies for all power levels studied. The U-Truss design concept, however, provided much lower transverse boom torsional natural frequencies. Whereas an IOC Space Station utilizing this design would not experience any structures and controls interaction, the same cannot be said for the growth power level. The 300 kWe system does not provide the desired decade of separation between the transverse boom natural frequency and the frequency of the rotary alpha joint controller bandwidth. The separation, in fact, is only half of the design goal.

TRANSVERSE BOOM FUNDAMENTAL TORSIONAL MODE FREQUENCY AS A FUNCTION OF POWER LEVEL



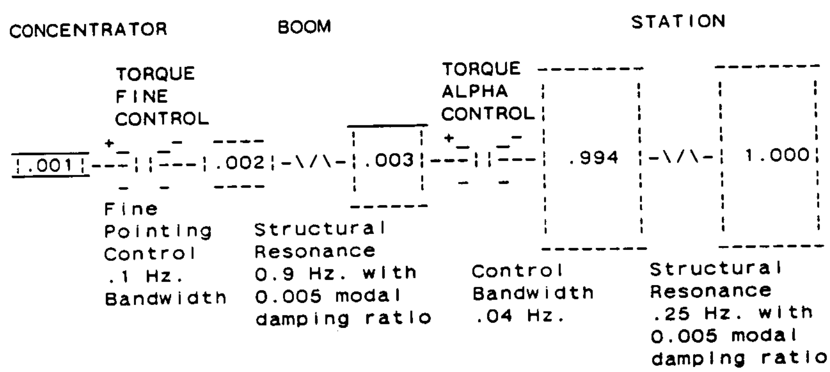
- RESULTS BASED ON 25 kWe MODULE SIZE
- 9 FT TRUSS SIZE USED AS POWER MODULE SUPPORT WHERE APPLICABLE

CONTROL OF CONCENTRATOR

The solar concentrator is to be pointed toward the sun with a wide angle of adjustment for each axis of rotation. The alpha joint provides continuous 360° tracking of the sun, and the fine pointing mechanism accounts for the 2° tolerance of the alpha joint. The concentration ratio at the receiver aperture can be several thousand suns and the concentrator focal point needs to be pointed accurately within 0.1 degree.

The vernier pointing control may operate in a high bandwidth near structural natural frequencies. A rule of thumb holds that controls should be well below structural frequencies to avoid oscillations. However, that rule applies for controls which "lock" a joint.

Stability and interactions of the vernier and coarse pointing controls are analyzed with a simplified torsional model of the station. The problem is simplified to consider only rotations about the alpha axis of rotation. Note that similar results are expected for the orthogonal beta axis.



CONTROL IS SIMPLIFIED PURE PROPORTIONAL PLUS DERIVATIVE

CONTROL TORQUE = PROPORTIONAL GAIN * (COMMAND - ANGLE) + DERIVATIVE GAIN * (INBOARD VELOCITY * M1 - OUTBOARD VELOCITY)

IF M1 = 0 ONLY VELOCITY OUTBOARD OF ALPHA JOINT ENTERS

M1 = 1 VELOCITY IS DIFFERENCE ACROSS THE ALPHA JOINT

COMMAND SIGNAL FOR ALPHA AND VERNIER POINTING IS FROM CONCENTRATOR CONTROL COMPUTER

ALTERNATIVE COMMAND SIGNAL FOR ALPHA JOINT IS FROM STATION GUIDANCE

IF CONTROL GAINS AND ADJUSTED HIGH, JOINT APPEARS "LOCKED"

IF CONTROL GAINS AND ADJUSTED LOW, JOINT APPEARS "NON LOCKED"

Based upon the simplified model several observations are made. Results may motivate undertaking more detailed analysis to verify their accuracy.

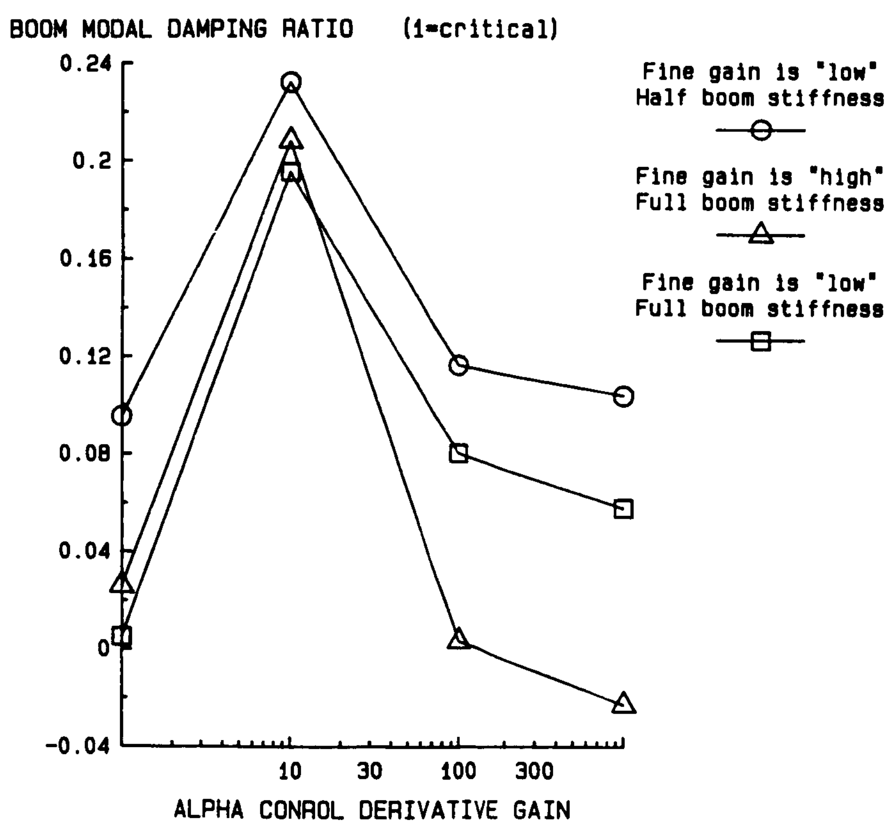
Comments on the results shown in the figure below are listed here. The control law derivative gain operates on the relative velocity across the joint, i.e., "M1" = 1.

1. The pointing controls can be a beneficial (although unintended) source of system damping. The increase in damping, above the small .005 assumed structural damping, is a result of the active control.

2. The pointing controls may operate in bandwidths near system structural frequencies. The boom need not be designed stiff to avoid control instabilities.

3. If the pointing control gain is too high, the control tends to "lock" the joint and beneficial damping is lost. In the worst case, the system is unstable.

BOOM MODAL DAMPING RATIO INTERACTIONS WITH CONTROL GAIN OF ALPHA GIMBAL



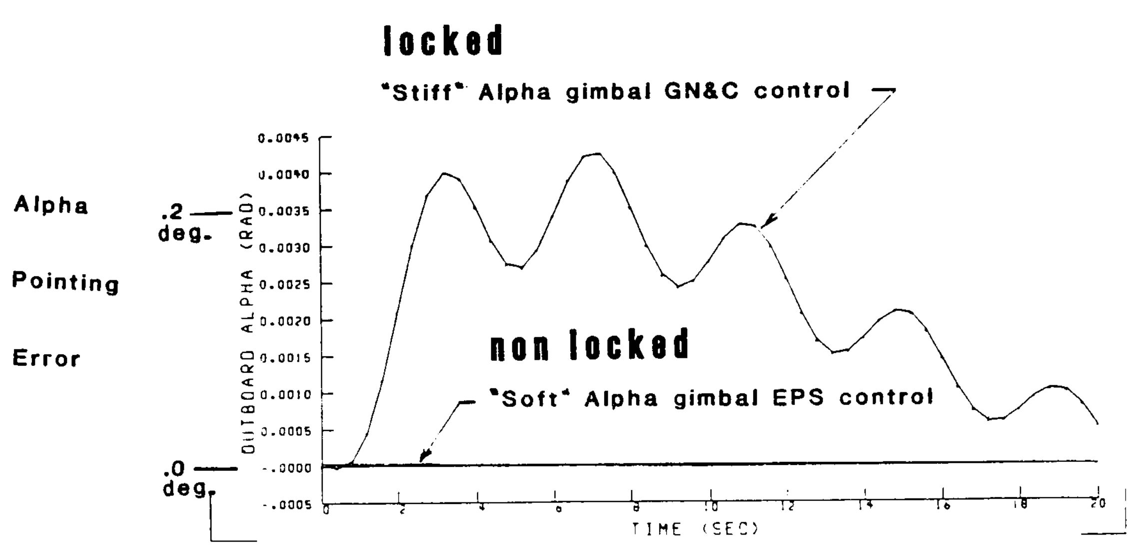
Derivative gain is normalized to 1 at low gain.

Less error crosses the alpha joint: a) if both joints work to reduce the same fine pointing error, and b) if disturbances can back drive the joints. Back drive joints can be natural vibration isolators, passively reducing disturbances from the station to the concentrator, removing the need for fast controls, and eliminating the potential for structural instabilities that can occur with too high gain.

The curves in the figure demonstrate control that eliminates the transmission of disturbances across the alpha joint. No error passes if:

1. The joint control uses derivative gain for outboard velocity only, i.e., (M1 = 0).

2. The COMMAND to the alpha joint is the fine pointing error and not a signal from station guidance.



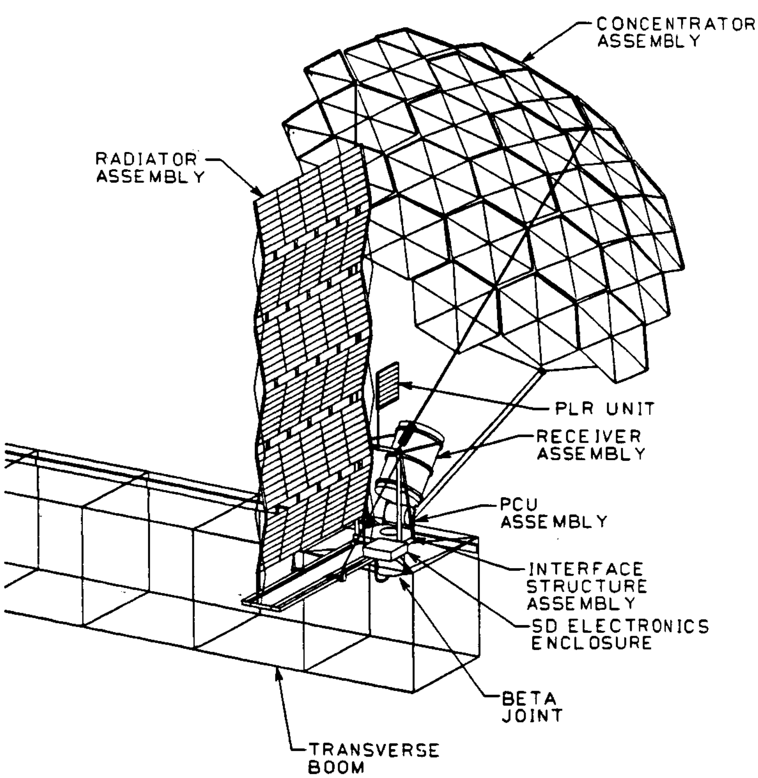
Response outboard Alpha gimbal to .0034 rps torsional disturbance to station

THE PARABOLIC OFFSET LINEARLY ACTUATED REFLECTOR

The conceptual design chosen as the baseline from the trade studies is the Parabolic Offset Linearly Actuated Reflector (POLAR) solar dynamic module.

The solar dynamic system consists of five major assemblies: concentrator, receiver, power conversion unit (PCU), radiator and interface structure assembly. The figure below reflects changes in the current design from the concept considered during trade studies. This includes most noticeably the utilization of a pumped loop radiator system instead of a heat pipe radiator. The module attaches to the Space Station structure outboard of the beta joint flange which mounts to the interface structure. The solar dynamic system interface with the power management and distribution system is outboard of the solar dynamic power module frequency converter and remote bus isolators.

The offset Newtonian concentrator consists of a segment of a parent parabola with a focal length to diameter ratio of 0.25 mounted offset from the parent parabolic axis of revolution. The receiver is tilted 53^{o} with respect to the parent parabolic axis of revolution to achieve a nearly symmetric receiver cavity flux distribution. The offset configuration, used successfully in RF applications has a low mass moment of inertia about the transverse boom. In addition, there are no serious primary or secondary blockage problems. The offset reflector does cause larger cosine losses than a symmetric Newtonian concept. The desirable symmetric flux distributions are also more difficult to achieve.



CHARACTERISTICS

MASS (CONCENTRATOR ONLY)
2418 LBS

DRAG (CONCENTRATOR ONLY)
2957 FT^2

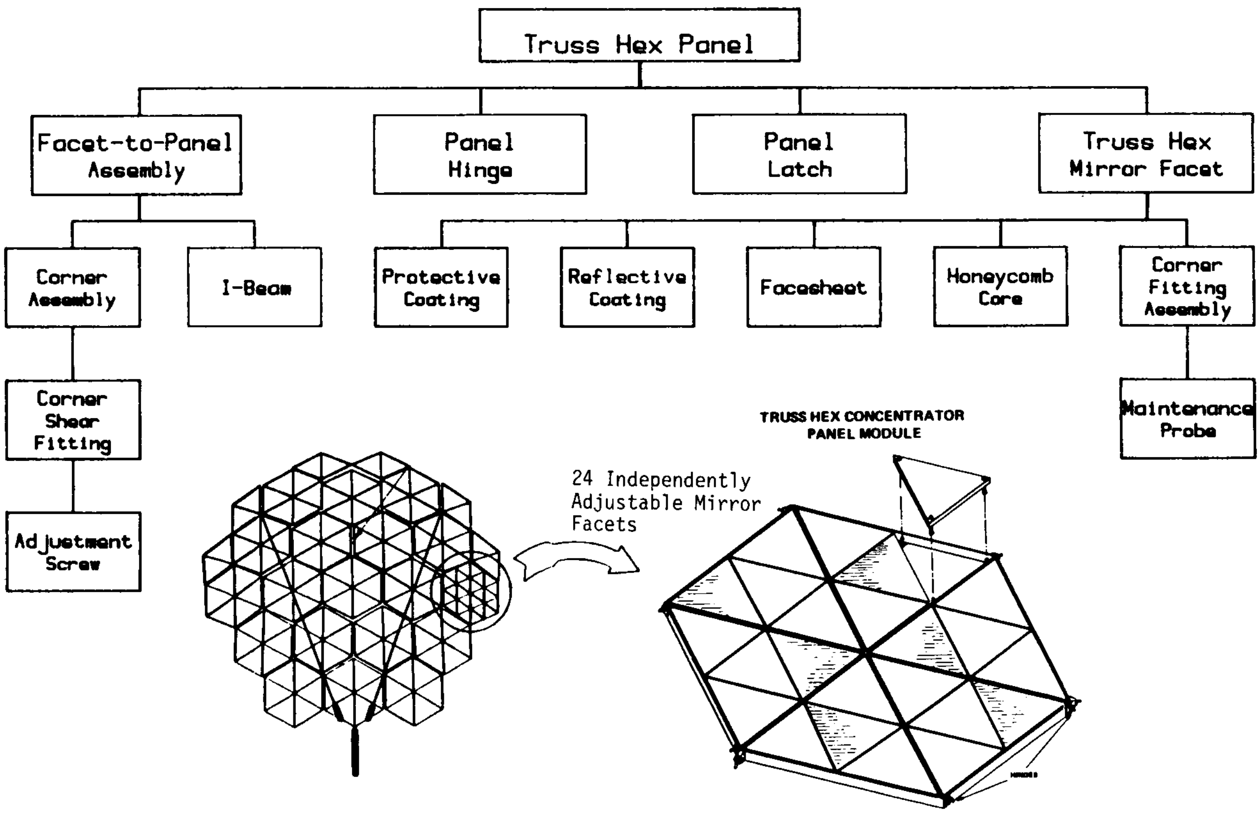
MASS MOMENT OF INTERTIA
(MODULE ABOUT TRANSVERSE BOOM)
0.5 $(10)^6$ LB.FT.S

SHUTTLE ORBITER PAYLOAD MANIFESTING
2 MODULES/LAUNCH

The solar concentrator is made up of an assemblage of 19 hexagonal panels. The panels are attached to each other with hinges and latches that are designed to perform two functions. The hinges and latches are first an assembly aid designed for either automated deployment or EVA assisted erection. After assembly of the 19 hexagonal panels into a single unit, the hinges and latches provide structural integrity. The hinges and latches are fabricated from aluminum.

The hexagonal panels are an assembly of I-beams and corner shear fittings to which triangular facets are attached. The hexagonal panel superstructure is entirely graphite/epoxy composite construction with the exception of the adjustment screws. The triangular facets are each approximately 3 ft. on a side. Constructed with a honeycomb core, graphite/epoxy composite facesheets, and a vapor deposited reflective surface, the facets weigh approximately 0.8 lbs./sq. ft. A protective coating applied over the reflective surface is required to reduce surface degradation. Focusing of the triangular facets is accomplished on the ground prior to packaging by means of the adjustment screws.

Solar Concentrator Hardware Tree



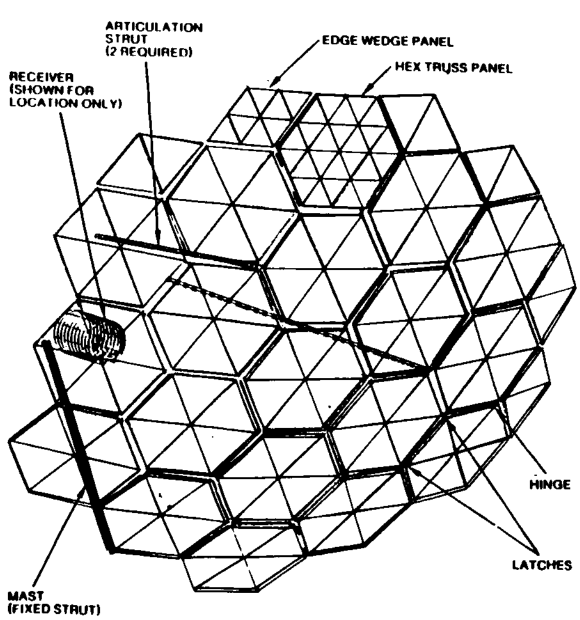
CONCENTRATOR SUPPORT STRUCTURE DESIGN AND ANALYSIS

The three strut solar concentrator support structure provides three degree of freedom vernier pointing capability by incorporation of linear actuators into two of the three tripod struts. This allows for solar vernier tracking by articulation of the concentrator. This also reduces the inertia that the actuator motor must overcome by requiring movement of only the concentrator. The drawback of the three strut tripod concentrator support system is the relatively poor structural dynamic characteristics exhibited by such a structure. Should one of the struts fail, there would exist no structure to support the concentrator in a stable manner.

An alternative to the three strut tripod concentrator support is the six strut tripod support system shown below. Static and dynamic structural analyses were performed to investigate the structural integrity of the three strut and six strut tripod support structures.

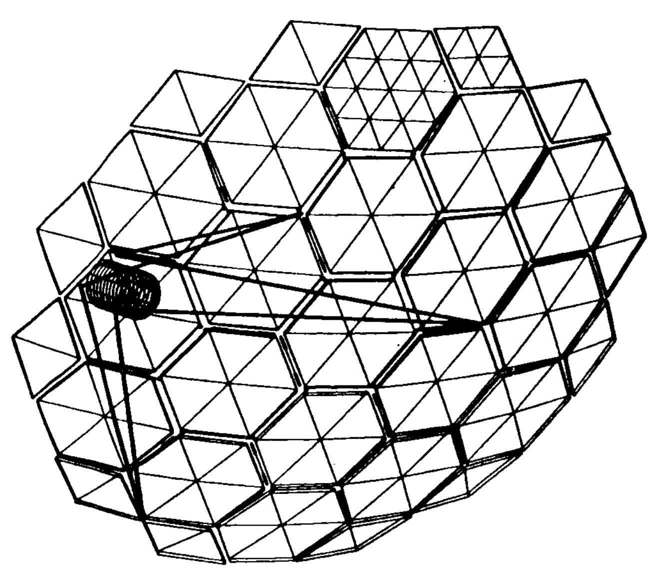
Pictorials of both concepts and their fundamental frequencies are shown below. The inside diameter and wall thickness of the three strut support structure were taken to be 3.0 in. and 0.15 in., respectively. The equivalent dimensions for the six strut support structure were 1.5 in. and 0.075 in.

3-STRUT TRIPOD CONCENTRATOR SUPPORT STRUCTURE



F_N = 0.271 Hz

6-STRUT TRIPOD CONCENTRATOR SUPPORT STRUCTURE

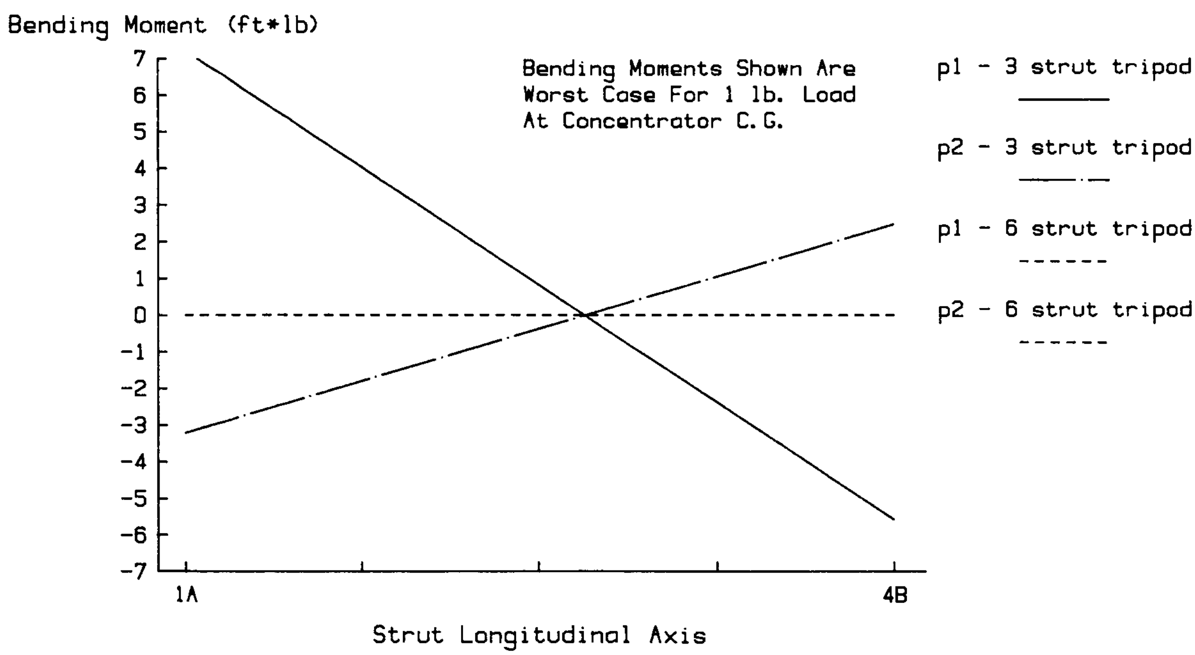


F_N = 1.46 Hz

A parametric linear static analysis of the candidate support structures were performed to determine their response to various load cases. By assuming the concentrator to be a rigid body relative to the support struts the structural performance of the two options was determined. Load cases where 1 lb. forces and 1 ft*lb moments were applied at the concentrator center of gravity were investigated. The results shown here are for the case where a 1 lb. force is applied parallel to the transverse boom axis with an inboard direction vector. Displacements, forces at the constraints, forces including axial, bending, and shear in the struts, and stresses in the struts were determined.

The worst case bending moments in the struts of the three and six strut tripods are shown plotted below. As seen, much lower bending moments are transferred through the six strut support structure. Moments transferred to the solar dynamic module mounting platform by the six strut support structure are calculated to be three orders of magnitude lower for the identical load case.

CONCENTRATOR SUPPORT BENDING MOMENTS

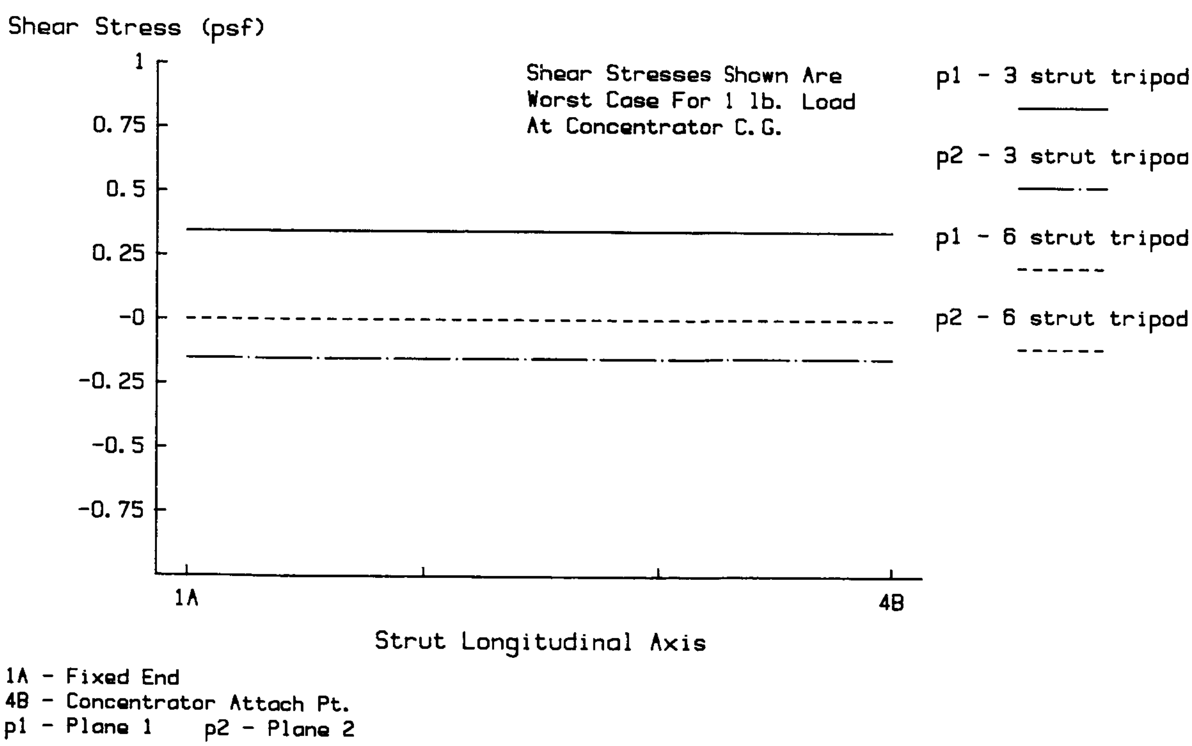


1A - Fixed End
4B - Concentrator Attach Pt.
p1 - plane 1 p2 - plane 2

The figure below shows the worst case shear stresses in the concentrator support structure struts (for the three and six strut tripods) for the 1 lb. force load case described previously. Not shown are the tensile and compressive forces in the struts which are in general an order of magnitude greater in the six strut tripod support system. These results along with the bending moments shown previously indicate that the six strut support structure is far more resistant to bending than the three strut tripod support. Hence, the six strut design, stiffer in bending, would minimize receiver spillage losses due to accelerations transmitted from the Space Station structure to the solar dynamic module.

The vernier pointing system design for the six strut tripod support still needs to be resolved. Solutions ranging from articulation of only the concentrator to articulation of the receiver/concentrator assembly are being investigated.

CONCENTRATOR SUPPORT SHEAR STRESSES



SUMMARY

The Parabolic Offset Linearly Actuated Reflector (POLAR) solar dynamic module was selected as the baseline design for a solar dynamic power system aboard the Space Station. The POLAR concept was chosen over other candidate designs after extensive trade studies. The primary advantages of the POLAR concept are the low mass moment of inertia of the module about the transverse boom and the compactness of the stowed module which enables packaging of two complete modules in the Shuttle orbiter payload bay.

The fine pointing control system required for the solar dynamic module has been studied and initial results indicate that if disturbances from the station are allowed to back drive the rotary alpha joint, pointing errors caused by transient loads on the Space Station can be minimized. This would allow pointing controls to operate in bandwidths near system structural frequencies.

The incorporation of the fine pointing control system into the solar dynamic module is fairly straightforward for the three strut concentrator support structure. However, results of structural analyses indicate that this three strut support is not optimum. Incorporation of a vernier pointing system into the proposed six strut support structure is being studied.

REFERENCES

1. McCormick, C. W., ed., "MSC/NASTRAN User's Manual", (Version 63) May 1983.

2. Housner, J. M., "Structural Dynamics Model and Response of the Deployable Reference Configuration Space Station", NASA TM 86386, May 1985.